COMPUTER NUMERICALLY CONTROLLED MILLING OF SHIP MODEL PROPELLERS

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Abstract

Shaping of sculptured surfaces such as propellers has traditionally been the domain of pattern makers and craftsmen. These highly skilled and experienced professionals translate designer's drawings into three dimensional shapes using templates and very frequently interpret designer's wishes on the basis of their own experience and skill. This traditional method of rendering propellers is very labour intensive, very time consuming and the results are very dependent on the individual pattern maker's skill and experience.

This paper describes traditional ship model propeller making, examines the advantages of model propellers milled under computer control and describes technology for Computer Numerically Controlled (CNC) milling of model propellers developed by Dominis Engineering.

1. Introduction

Sculptured surfaces are complex curved surfaces which cannot be defined by means of analytical formulae or equations but are defined by a set of discrete points. We can find these types of surfaces on many objects we encounter, for example, car bodies, parts of aircraft fuselage, airplane wings, ship's hulls, aircraft propellers, keels of sail boats, marine propellers, hydraulic turbine blades etc. Of all sculptured surfaces, propeller blades and turbine blades are the most complex ones.

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Most ship model propellers have traditionally been made in two ways:

a)
- Carving patterns for pressure and suction sides of propeller blade,
- preparing blank blades from bar stock,
- copying the patterns to the blades on the three dimensional pantograph and
- hand finishing the blades by filing.

b)
- Carving a pattern for casting of model propeller,
- casting model propeller,
- drilling all blades on a pitchometer at locations and to depths specified in the table of offsets and
- hand finishing the blades by filing.

The major areas where we find inaccuracies on hand finished propeller blades are at the leading and trailing edges, at the tip and in the regions between the pre-drilled stations. The regions between the stations which have been pre-drilled on the pitchometer are essentially undefined. The propeller craftsman is required to join these stations with a smooth surface. The only criterion is that all contours should blend in smoothly. When shaping these undefined areas the craftsman must rely on his past experiences in propeller manufacturing.

The edges of a blade are shaped by hand to match manually-shaped sheet metal templates. Templates are cumbersome to use and can be used only to verify if the finished surface matches the profile of the template. If the surface does not match the profile of the template, the craftsman must visually inspect the mismatch and decide on the corrective action.

It is clear that the quality of the resulting surface will depend greatly on the skill of the craftsman. Moreover, even when a set of blades is made by the same experienced craftsman, there will be significant variations between blades. Waviness of the blade surface will create problems with both static and dynamic balancing and decrease propeller efficiency. Inaccuracies at the leading edge will induce cavitation and increase propeller generated noise.

In an effort to resolve some of these problems, and to satisfy new requirements for high precision propellers, Dominis Engineering has invested over four years in research and development of Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) methods aimed at eliminating the inaccuracies in propeller manufacturing. This work has resulted in the development of a new manufacturing technology capable of milling model propellers to their final form. Different aspects of this technology will be discussed and the manufacture of a series of model propellers for Defence Research Establishment Atlantic will be described in the subsequent sections of this paper.

2. Propeller Geometry

We were contracted to manufacture a series of four model propellers. Each propeller had five controllable pitch blades. Radial view of one of the model propellers in this series is shown in Figure 1. Since cavitation tunnel tests were going to be performed only with blades set at the design pitch, there was no need to provide for changing of blade pitch. Consequently the hub for the model propeller was designed in such a way that propeller blades could be locked in place at the design pitch. All four propellers had the same basic parameters with small variations in pitch, camber and skew distributions. Only twenty radial profiles in non-dimensional form were specified for each propeller blade type. Sectional profiles of propeller blades were specified with blunt edges. To complete each profile, blunt edges had to be replaced with elliptic-hyperbolic edges blended to the given profile. Variable radius fillet was defined at the leading and trailing edges and at three more locations along the chord.

2.1 Propeller Geometry Data Base

The first step in the process of Computer Numerically Controlled (CNC) milling of propellers is creation of propeller geometry data base. This data base must define unambiguously all propeller surfaces (blade, fillet, palm and hub), their normals and curvatures. Procedures for creation of propeller geometry data base largely depend on the information supplied by the propeller designer. Constant dialogue between the designer and the manufacturer clarifies the design and often leads to its improvement. This dialogue and creation of an exact propeller geometry data base insures that designer's intentions are correctly implemented and that the manufactured propeller represents what the designer wanted and not what the manufacturer was capable of producing. Such exact data base is also required for CNC milling since numerically controlled machines cannot work with fuzzy geometrical entities.

The first step in creating propeller geometry data base consists of entering into the CAD system all the input data supplied by the propeller designer. Once entered in the CAD system this input data can be critically evaluated. Quality of each radial profile supplied is checked using three criteria: continuity of data, occurrences of unwanted inflection points and occurrences of abrupt changes in curvatures.

All data in the propeller geometry data base are entered at full scale. Various tools for checking and modifying propeller data are available in the CAD system. For example: computation of curvatures and normals at any point on the blade profile (see Figure 2), interpolation and blending of a new radial profile between the existing profiles, computation of any axial profile of the blade etc. CAD system also has extensive graphic capabilities for display and plotting of selected portions of the data base.

2.2 Creation of Propeller Blade Edges

All radial blade profiles were specified with blunt edges (see Figure 2). On each profile side and at each edge a conic section had to be fitted exiting normal to the chord and matching the profile either at a given point with given slope angle or at two given points. The conic is mostly an ellipse or a hyperbola and hence the name elliptic-hyperbolic edge (see Figure 3). Note that it is not always possible to fit such an edge and a dialogue with the designer becomes necessary. A final smoothing of the edges removes possible curvature steps at the meeting points (see Figure 4).

2.3 Creation of Propeller Blade Fillet

During the process of creating variable radius fillet intersections and tangencies between three curved surfaces have to be found. They are: intersection between the blade and the hub, tangency between the fillet and the blade, and tangency between the fillet and the hub.

A constant radius fillet surface and associated tangency lines can be generated by rolling a sphere around the blade root while keeping it in touch with both the blade and the hub. Figure 5 shows tangency lines with the hub around the trailing edge for constant radii fillets of 0, 12, 15, 20, 25, 30, 35, 40, 45 and 50 mm.

A variable radius sphere rolled around the root of the blade creates a variable radius fillet. The variation of the fillet radius as specified by the designer was used to construct the appropriate tangency line (see Figure 5). Tangency line with the blade and the locus of fillet centers were constructed in a similar fashion.

Note that a sphere, even with variable radius, will always generate a unique fillet. Some other fillet concepts might require a different approach.

2.4 Propeller Milling Data Base

Only after the propeller geometry data base has been created can we proceed to create the propeller milling data base. Propeller milling data base is created automatically by the CAD system. It contains additional radial profiles of the blade, additional fillet definition locations and additional data for definition of propeller tip. This additional data is necessary for computation of cutter center path.

Once the cutter center path is created it has to be checked for interference with the propeller, fixture or milling machine in question. Due to the peculiar hub shape a part of the leading edge was not accessible by the ball nose cutter (perpendicular to paper plane in Figure 6a) when the face side was up. Swivelling of the propeller by -40 degrees around the blade axis cleared the leading edge but obscured the trailing edge (see Figures 6b and 7). It was found that a tilt of 17 degrees around transversal axis was necessary and sufficient to clear the trailing edge (see Figures 6c and 8).

A fixture was built to implement these angles when the hub is mounted for milling. Sine tables were not considered appropriate for the machining centre used. Of course, when the propeller was mounted back side up, the angles by which the propeller data were to be rotated changed to swivel of -40 degrees and tilt of -17 degrees.

3. Model Propeller Assembly

Each model propeller assembly is made out of several parts. Preparation of each assembly involved many operations, some on conventional machines and some on CNC machines. Here is a brief summary of the process:

- The hub and hub cap were made out of roll stock and their shape turned to rough profile.
- Keyed hole 20 mm in diameter was drilled and broached in the center of the hub to accommodate mating of the hub cap and the drive shaft.
- Holes for trunnions seats and trunnion taper pins were drilled in the hub.
- Trunnions were made out of roll stock. They were turned to size to fit into appropriate trunnion holes in the hub.
- Slots for fitting of blade blanks were milled in the trunnions.
- All trunnions and their corresponding holes in the hub were numbered.
- Trunnions were fitted into their positions in the hub so that the holes for tapered pins could be reamed.
- Template for the hub and hub cap profile was milled on the CNC milling machine.
- Hub, hub cap and trunnions were contoured on the lathe using hub profile template (see Figure 9).

- Blade blanks were cut from the bar stock. Sides of the blade blanks to which trunnions were to be attached were squared, milled, drilled and tapped to allow mounting of trunnions.
- Blade blanks were mounted on a compound angle fixture to allow dressing of the blank for fitting of the trunnion and to contour the blade overhang (see Figure 5).
- Blade overhang was milled.
- After the milling of blade overhang, the excess material around the perimeter of the blade blank was trimmed on the band saw (see Figure 10).
- Each blade blank was mated with its trunnion and bolted together (see Figure 11).

4. Fixtures and Tooling

The milling machine used for the manufacture of this series of model propellers was a three axes Mitsui Seiki VR3A vertical CNC machining center. Since the milling machine available was capable of only three axes simultaneous contouring, an elaborate compound angle fixture had to be designed to allow milling of both sides of the blade without interference between the tool shank and propeller hub. Also, since the propeller blades had to be milled one side at the time, appropriate support to the blade had to be conceived to prevent the tool from bending the blade out of shape during milling.

At first a low melting point alloy (Cerrotrue) was used in all operations. However, due to thermal deflection of the blade it was retained only as a base support during roughing and supplemented with a stable, nonshrinking epoxy (Ren-shape 360) for final stage of milling.

Selection of the tool diameter depends on the minimum radius of curvature that is found on the blade surface. Three sizes of ball nose cutters were used. One half inch diameter for rough cut milling of blade surface and fillet, one quarter inch diameter for final cut milling of the blade surface and one tenth of an inch diameter for final cut milling of the fillet. The finishing cutters were single lip type.

The blades, including the fillet and the palm, were rough cut to 0.025 inch oversize, in 60 cutting paths per side. Final cut to size run in 300 passes per side. The distance between passes was 0.017 inch resulting in a scallop height of less than 0.0003 inch when cut with a quarter inch diameter ball nose cutter.

$$\text{Scallop height} = \frac{(\text{distance between passes})**2}{(4.*\text{cutter diameter})}$$

5. CNC Milling Process

Out of the many facets of this milling process, two were important for the successful operation.

In standard usage the NC programmers, manual or computerized, tend to let the machine run at a constant feed rate. To maximize the throughput and at the same time to maintain the accuracy it is necessary to assess the dynamic behaviour of the machine and adapt the feed rate to the local curvature avoiding overshoot. Thus the machine runs at a variable feed rate, running fast across the blade and slowing down when turning around the edges.

The final face side was milled first. Under ideal conditions the propeller would be flipped over to back side up and the milling would continue. However, due to even small inaccuracies in the fixture or in the hub bore and faces, the two sides of the blade could mismatch. Since this would not be acceptable a scheme to detect and correct possible mismatch was devised.

When the face side was completely milled and prior to taking the assembly off the fixture, up to five (minimum three) tooling balls on stems were glued to the face side sticking out over the contour. The center coordinates of each tooling ball were carefully indicated and noted. The assembly was then flipped and mounted back side up. The center coordinates of each ball were again carefully indicated and noted. The differences between where the tooling balls should have been (under ideal conditions) and where they actually are (under real conditions), are then used to find the best (in the least square sense) three linear shifts and three Euler angles which, when applied to the ideal cutting data, would cause both sides of the blade to match. This done, the tooling balls are removed, the epoxy support is applied and the milling continues.

6. Conclusions

Three axes milling machines have their limitations in milling propellers. The main handicap is the necessity to mill first one side and then the other side. To ensure exact matching of the face and the back of the blade accurate measurement of blade position before and after flipping is necessary. Using these measurement and knowing where should the blade be under ideal conditions, allows computation of the adjusted tool path which results in perfectly matched blade face and back.

Five axes milling machine will allow milling of propeller blades in one setting. On the milling machine with two rotary tables at right angles to each other, hub with the blade blank would be mounted on the shaft in the vertical rotary table so that blade blank would be free standing without any support. This type of set up allows the blades to be milled in one pass from tip to root without roughing, however the milling machine has to be capable of five axes simultaneous contouring.

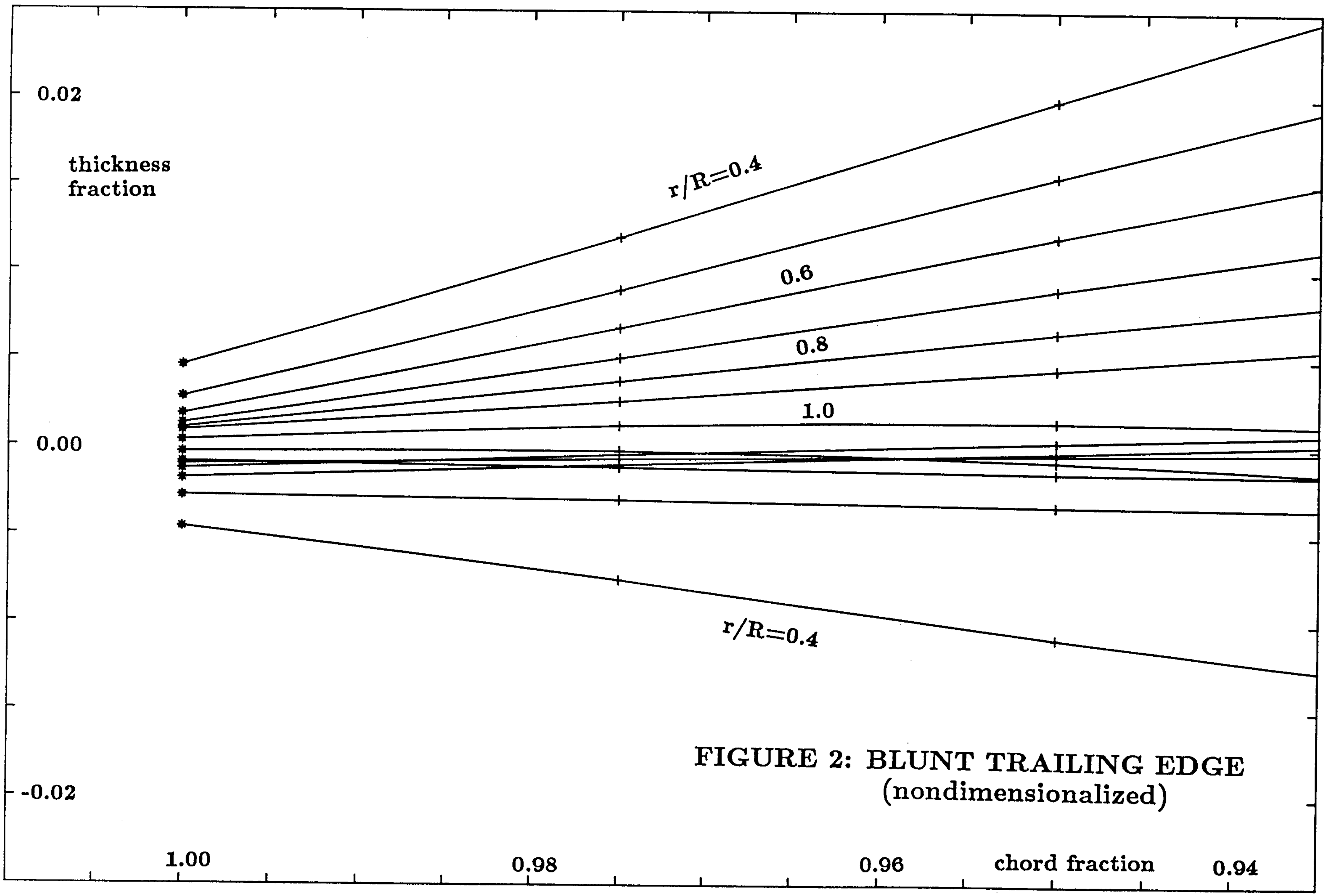


FIGURE 2: BLUNT TRAILING EDGE
(nondimensionalized)

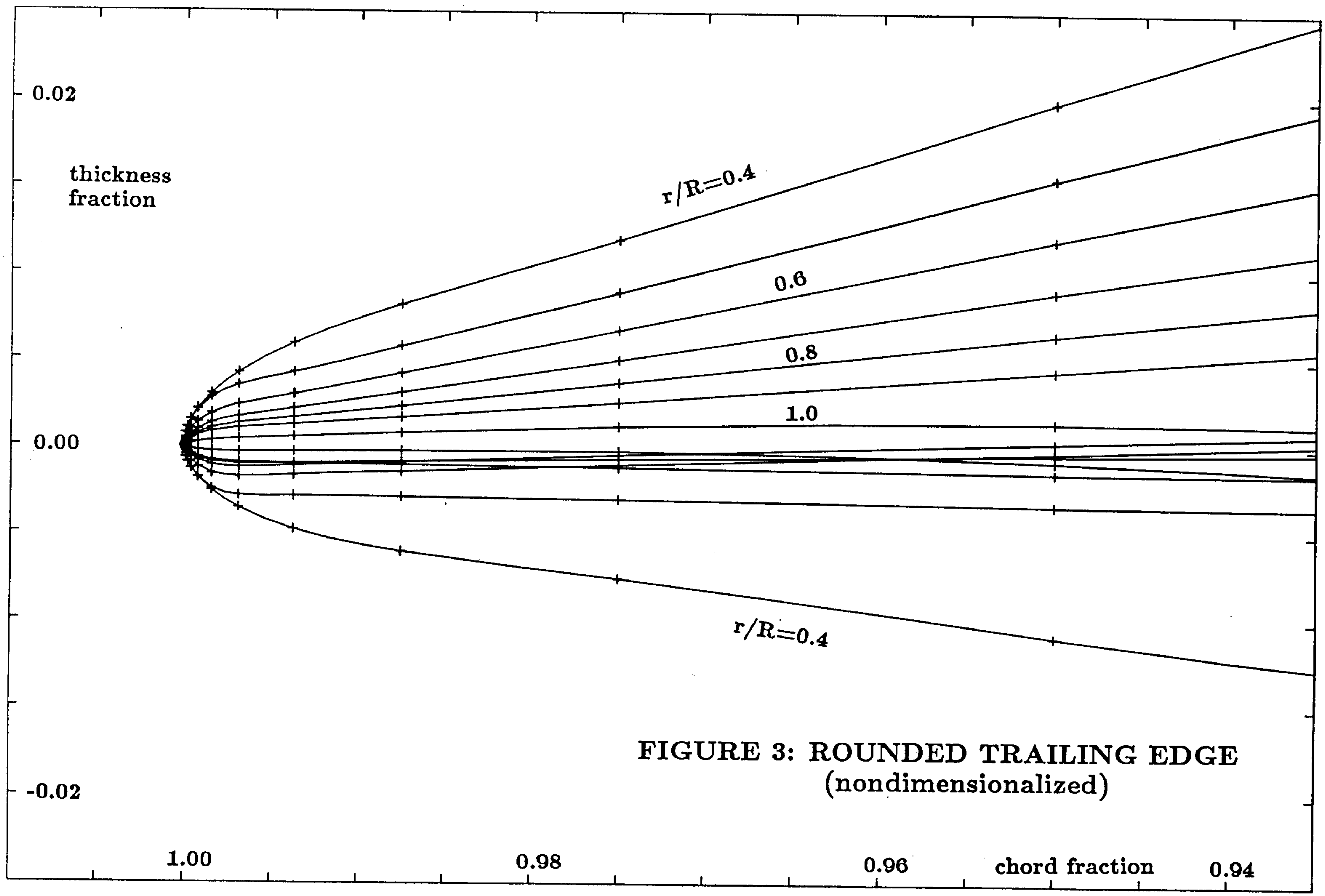


FIGURE 3: ROUNDED TRAILING EDGE
(nondimensionalized)

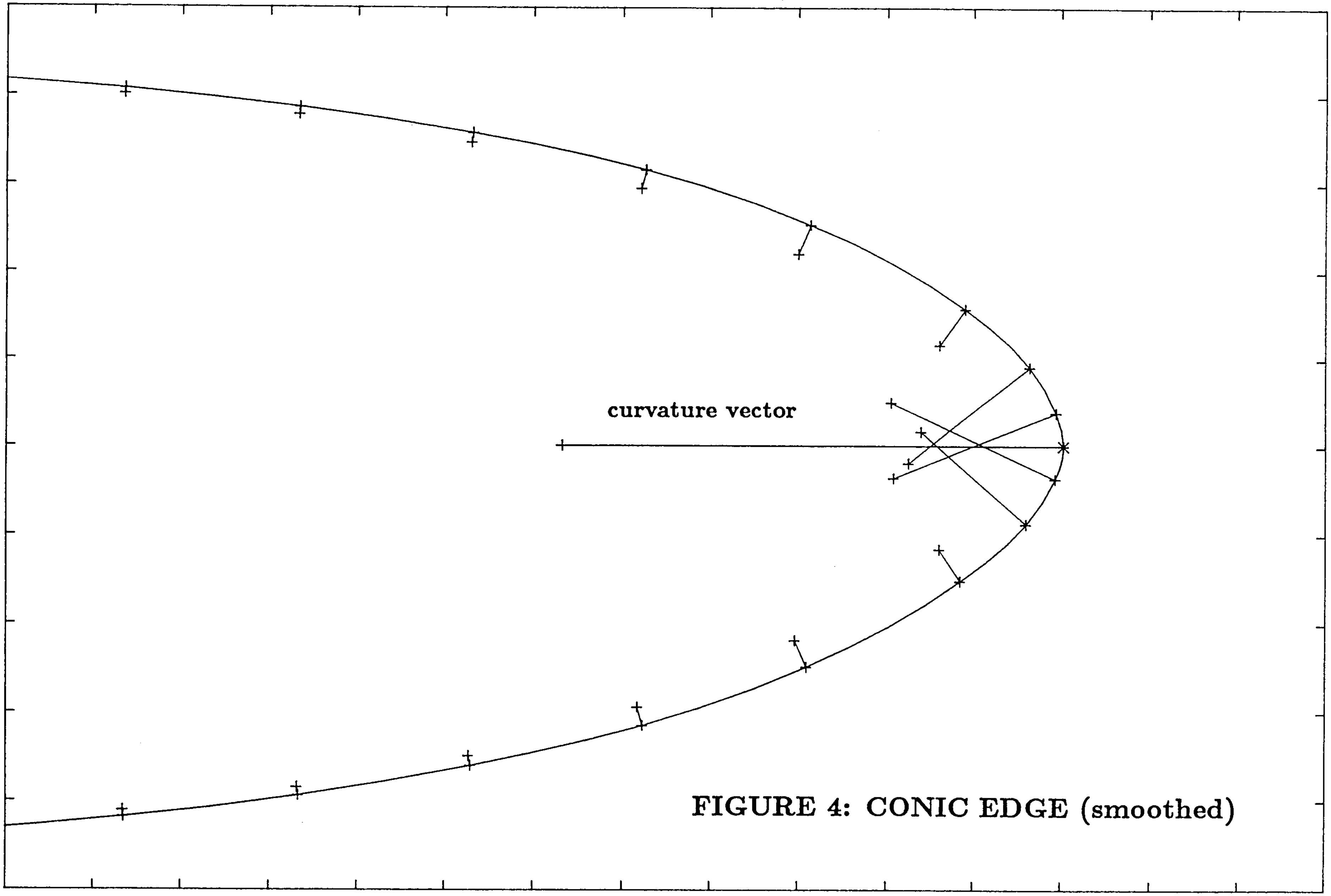


FIGURE 4: CONIC EDGE (smoothed)

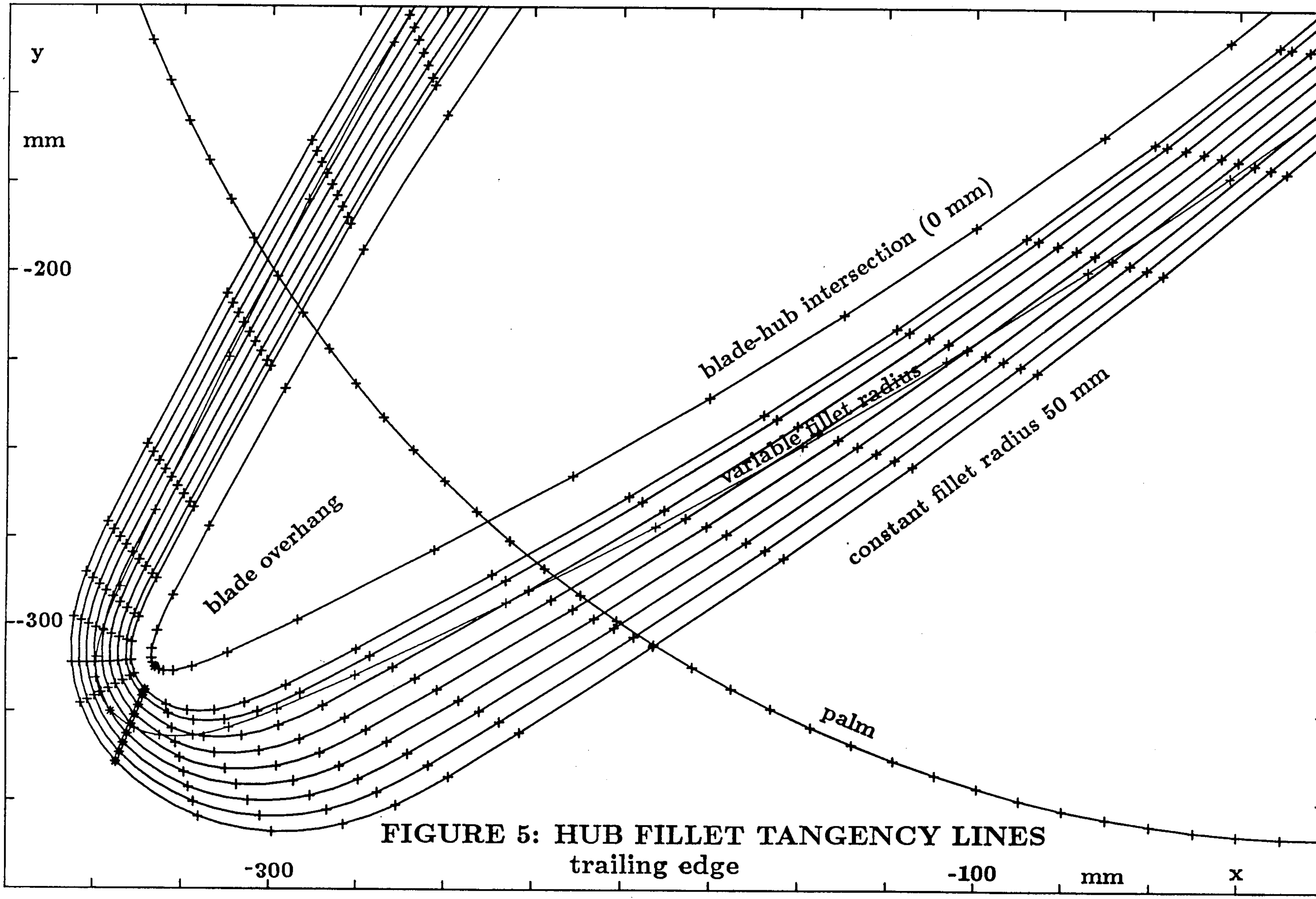
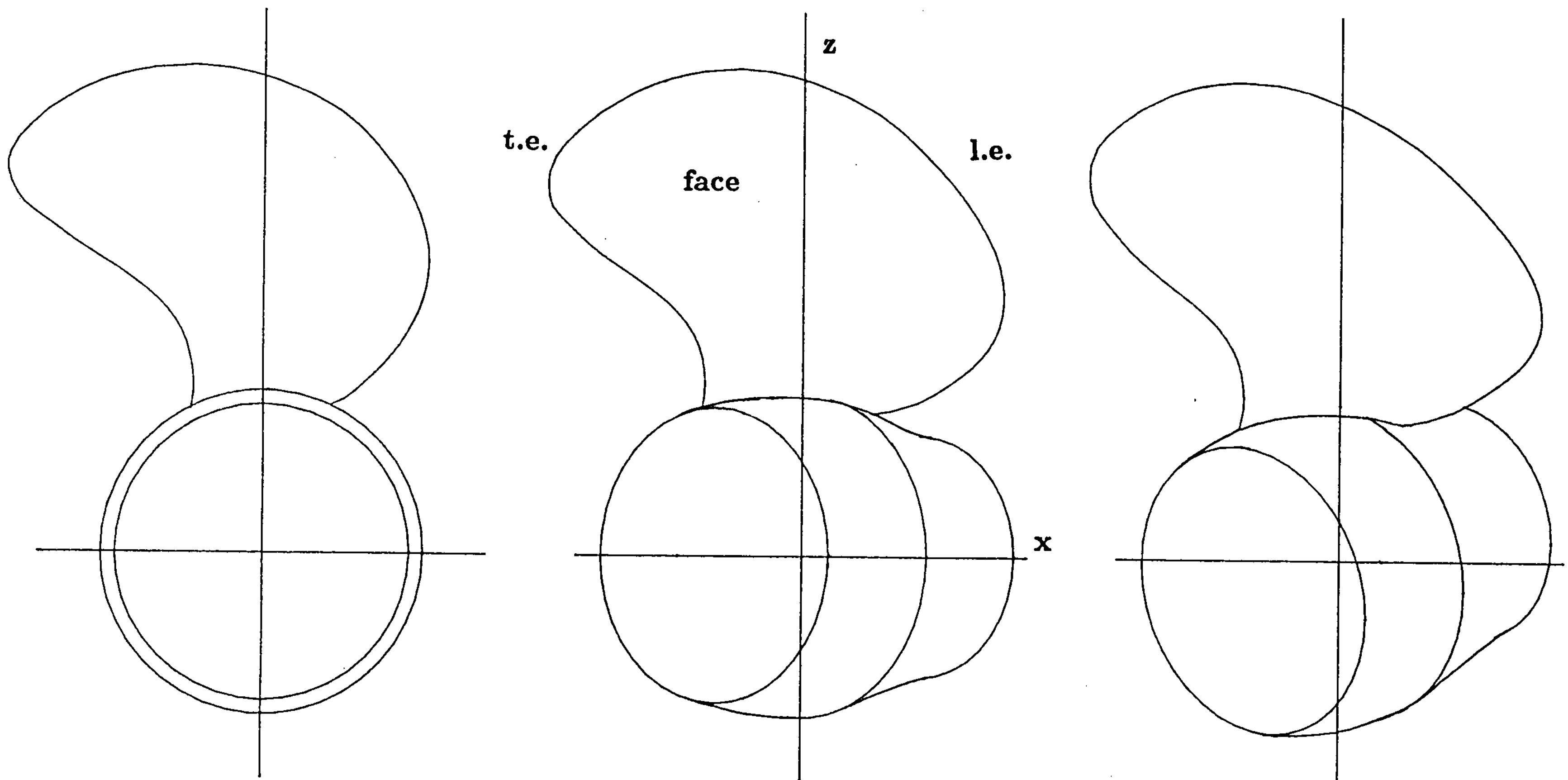


FIGURE 5: HUB FILLET TANGENCY LINES
trailing edge

FIGURE 6: FILLET HUB INTERFERENCE (face up)



6a: swivel 0° around z-axis and
tilt 0° around x-axis
l.e. interference

6b: swivel −40° around z-axis
tilt 0° around x-axis
l.e. cleared
t.e. interference

6c: swivel −40° around z-axis and
tilt 17° around x-axis
l.e. cleared
t.e. cleared

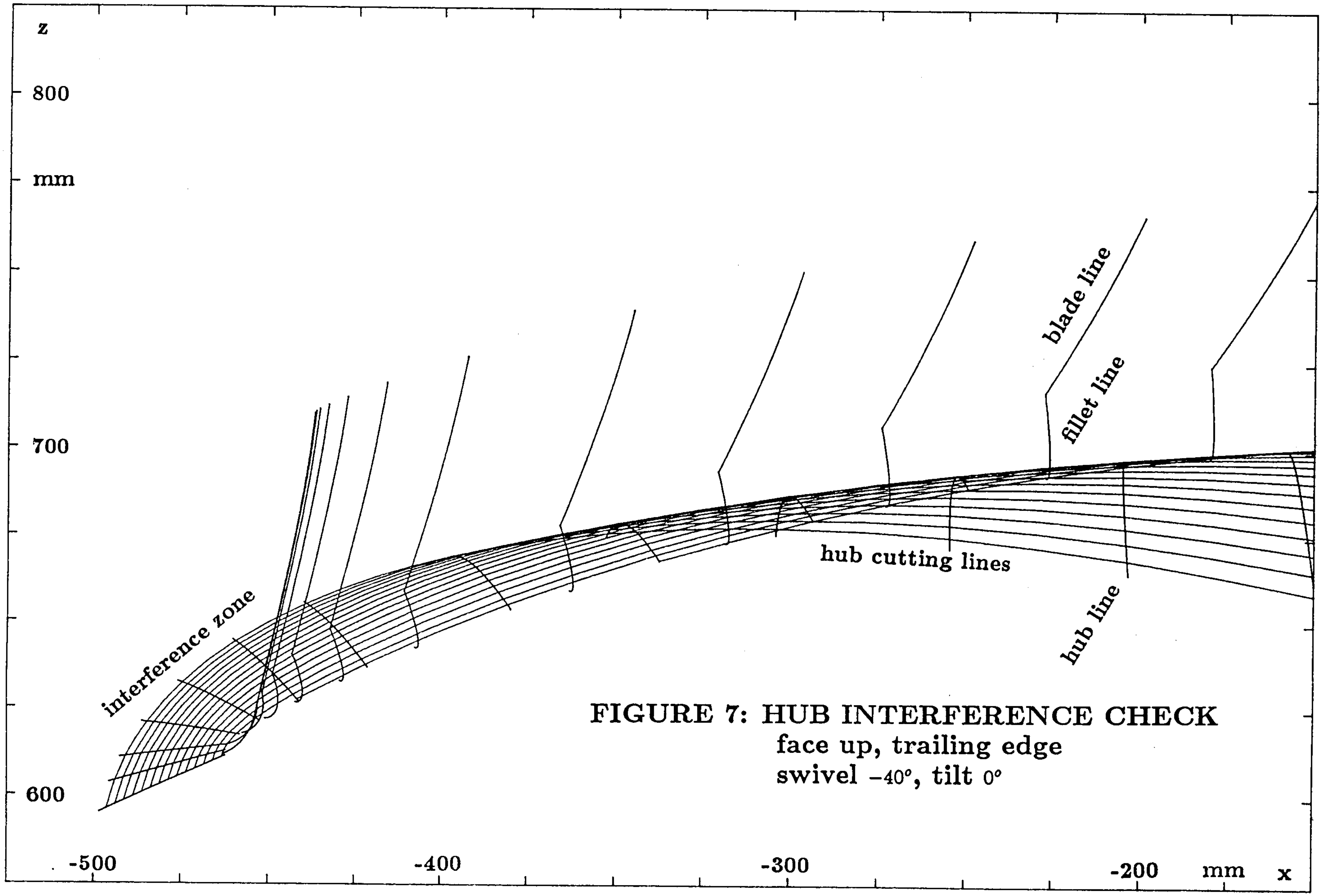


FIGURE 7: HUB INTERFERENCE CHECK
face up, trailing edge
swivel −40°, tilt 0°

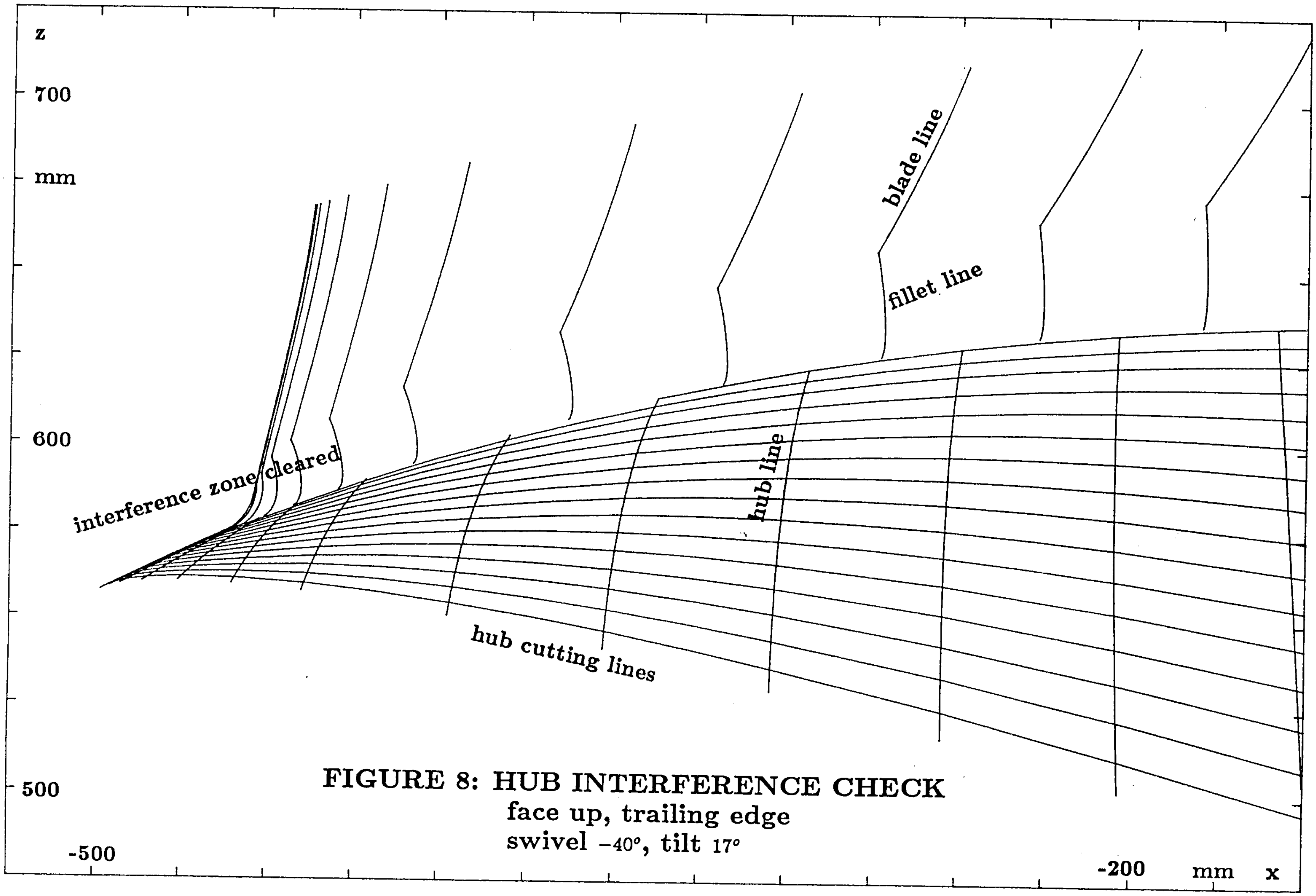


FIGURE 8: HUB INTERFERENCE CHECK
face up, trailing edge
swivel –40°, tilt 17°

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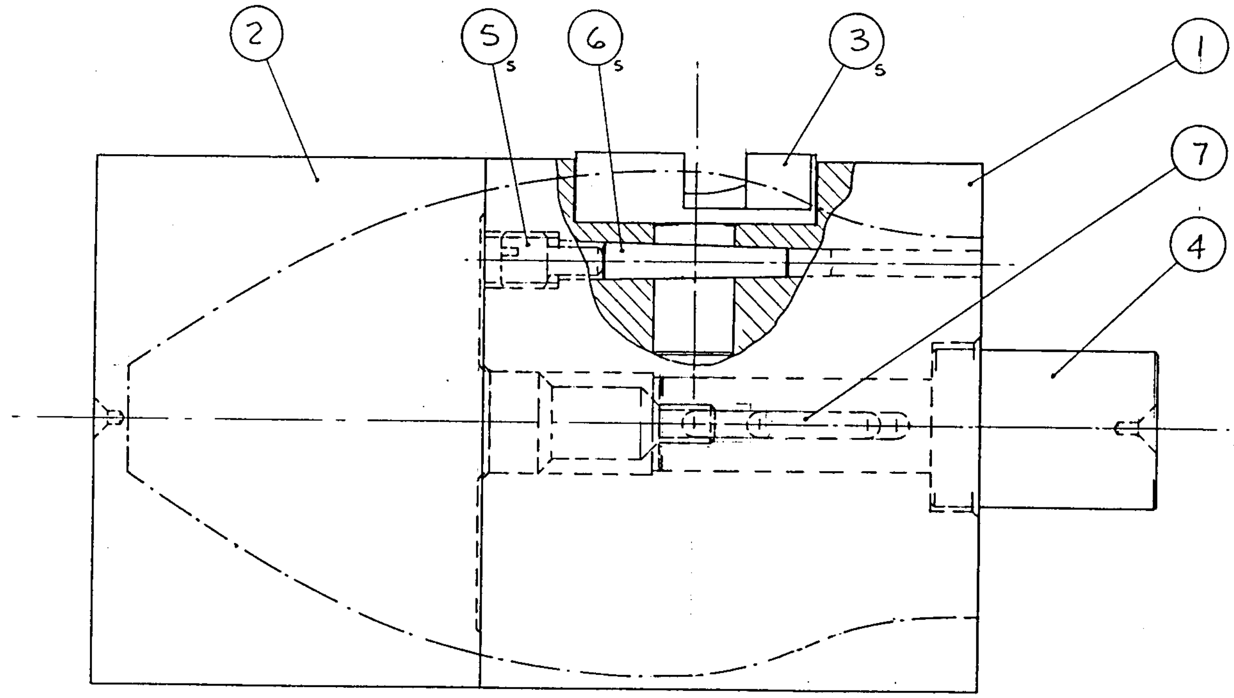
B	PICTORIALLY CHANGED. N.T.S. ADDED	11th NOV 88

FIGURE 9: ASSEMBLY READY FOR PROFILING



NOTE:
COMPONENTS TO BE PROFILED AS AN ASSEMBLY.

ALL COMPONENTS AND THEIR POSITIONS TO BE PERMANENTLY IDENTIFIED

7	1		KEY. SQUARE M6 × 30 SPAE-NAUR # 132-114
6	5		TAPER PIN M6 × 40 SPAE-NAUR # 238-342
5	5	A030-3-011	RETAINING SCREW
4	1	B030-3-008	ASSEMBLY SHAFT
3	5	A030-3-004	TRUNNION
2	1	B030-3-003	BOSS
1	1	B030-3-002	HUB

DOMINIS ENGINEERING LTD.

MATERIAL	TITLE: PROFILING ASSY.
FINISH	
DRAWN 3rd NOV 88 · D.P. · TOL.	DRAWING NUMBER: B030-2-012
USED ON	SCALE N.T.S. · REVISION B · SHEET 1 OF 1

K+E CRYSTALENE

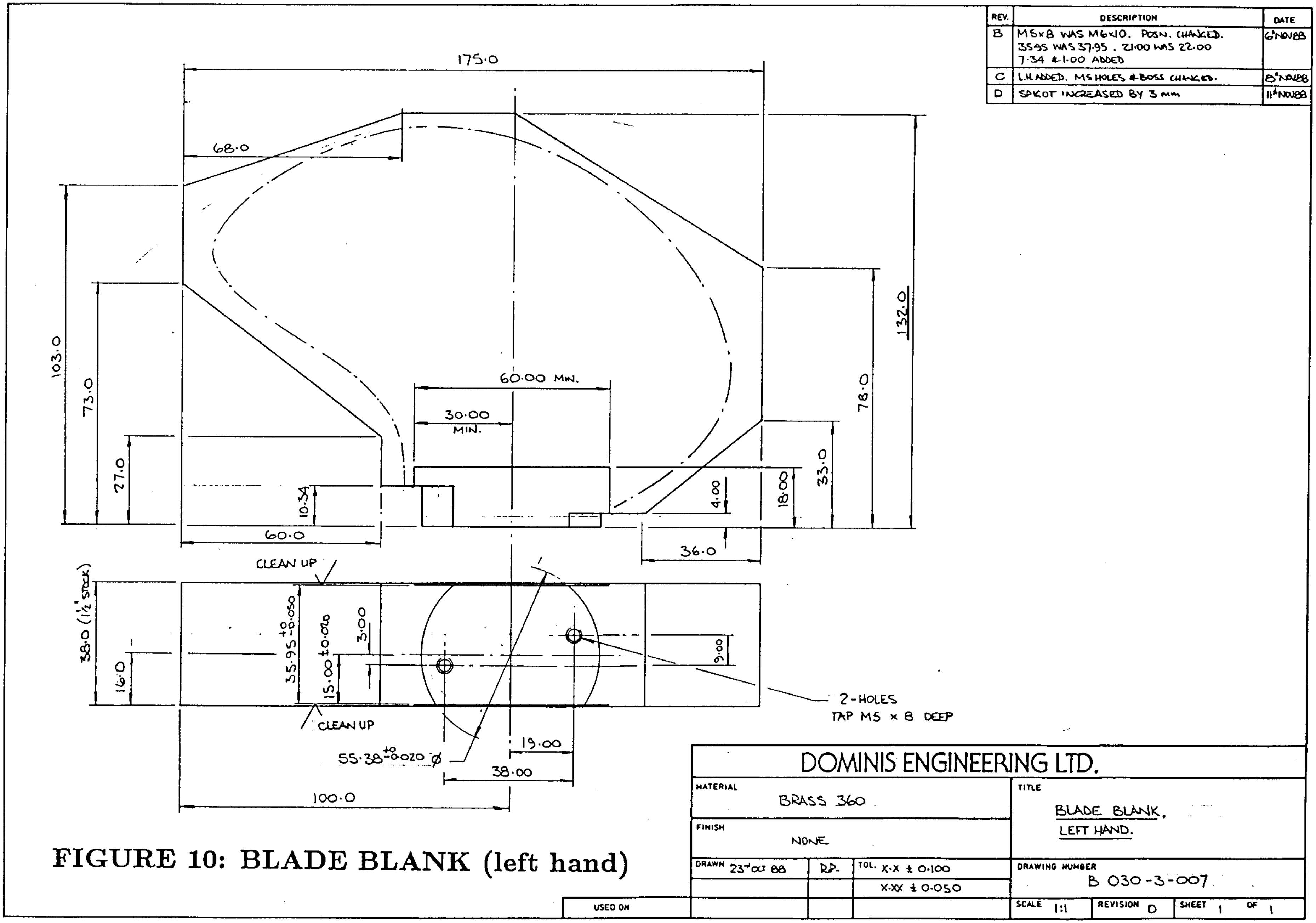
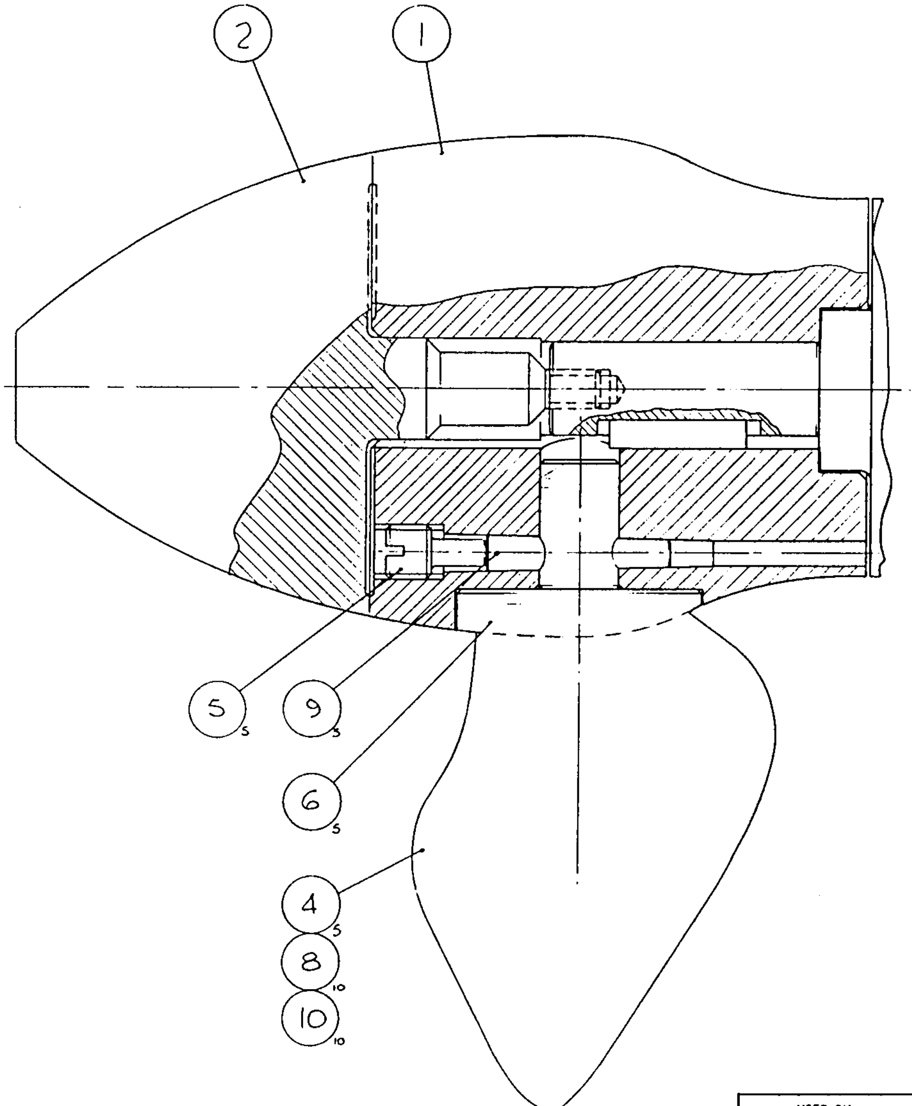


FIGURE 10: BLADE BLANK (left hand)

K+E

REV.	DESCRIPTION	DATE
B	ITEM 10 ADDED	11th NOV 88

FIGURE 11: PROPELLER ASSEMBLY



23	1	B030-3-010	ALIGNMENT HUB.	
22	1	B030-3-008	ASSEMBLY SHAFT.	
21	1	B030-3-006	HUB INDEXING JIG.	
20	1	B030-3-005	TRUNNION MACHINING JIG.	
			TOOLING	

11				
10	10		DOWEL M4 x 10 SPAE NAUR # 238-212	STEEL
9	5		TAPER PIN M6 x 40 LONG SPAE NAUR # 238-342	STEEL
8	10		SCREW M5 x 12 LONG FLATHEAD SPAE NAUR # 373-206	ST. STEEL
7				
6	5	B030-3-015	TRUNNION, LEFT HAND	
5	5	A030-3-012	PLUG, TAPER PIN	
4	5	B030-3-007	BLADE BLANK, LEFT HAND	
3				
2	1	B030-3-003	BOSS	
1	1	B030-3-002	HUB	
ITEM	No	DRG. No	DESCRIPTION	

DOMINIS ENGINEERING LTD.

MATERIAL —			TITLE PROPELLER ASSY.
FINISH —			
DRAWN 9th NOV 88	D.P.	TOL. x·xx / x·xxx	DRAWING NUMBER B 030-2-001
USED ON			SCALE — REV. B SHEET 1 OF 1

TRANSTEX 15 100-8-79